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A Study of the Potential Interference Between Satellite and Terrestrial Systems in the 28 GHz Band

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Abstract

The Federal Communications Commission (FCC) of the United States completed a Negotiated Rulemaking Committee in September, 1994 to determine methods for frequency sharing of the 27.5 to 29.5 GHz spectrum between terrestrial Local Multipoint Distribution Service systems and Fixed Satellite Service systems. The committee concluded that based on current commercially proven technology, these services could not share the same spectrum, due to expected unacceptable levels of mutual interference. Analysis and laboratory and field tests performed by NASA's Lewis Research Center contributed technical data which was used to support this conclusion. NASA's results indicate levels of carrier-to-interference ratios (C/I) which create perceptible degradation, the levels of C/I which might be expected in typical operational scenarios, and the level of reflected signals which might be found in the vicinity of transmitting FSS ground terminals.

Introduction

In April, 1994, NASA's Lewis Research Center was requested to provide technical assistance to the FCC Negotiated Rulemaking Committee (NRC) convening July 26, 1994, to consider frequency sharing of the 27.5 to 29.5 GHz band between terrestrial Local Multipoint Distribution Service (LMDS) systems and Fixed Satellite Service (FSS) systems. This request was based on NASA Lewis's expertise in Ka-Band satellite systems, which includes the development and operation of the experimental Advanced Communications Technology Satellite (ACTS), and experience in television interference assessment and testing, which dates back to the late 1960's. NASA Lewis responded by proposing several laboratory and field tests which could be completed in time for consideration by the Committee, and by performing analyses of potential carrier-to-interference ratios (C/I) in an operational scenario.

Three sets of results presented below summarize the outcome of these tests and analyses. The operational scenario analyses consider several combinations of FSS and LMDS systems and determine C/I levels which might be expected within an LMDS operating area due to an FSS uplink transmission at the same frequency. The laboratory tests used digitally-modulated interferers of several bandwidths to subjectively assess the C/I at which interference could be perceived by television viewers. The field testing consisted of measurements of the signal reflections in the vicinity of an operating ACTS ground terminal in order to assess the potential for interference levels in a reflection environment.

The LMDS/FSS Interference Problem

The LMDS systems being studied would provide a two-way point-to-multi-point and multi-point-to-point service. The primary service envisioned is a video distribution from a central hub in a cellular architecture, with return links from users to the central cell hub for voice, data, and video conference services. 1000 MHZ of spectrum was proposed for each of two licensees per area, covering 27.5-28.5 GHz and 28.5-29.5 GHz. Each 1000 MHZ could contain, for example, 50 FM video channels. The LMDS video distribution system in Brighton Beach, NY, operated by the Suite-12 Group/CellularVision of New York, which was operational under an experimental license at the time of the NRC, represents a typical LMDS system[1,2]. Other systems considered for analyses included VideoPhone/Endgate and Texas Instruments. These systems include combinations of services including FM, AM, and digital video, and digital voice and data. Cell radius varies from less than 1 km to 5 km, depending on the type of service, subscriber density, and regional climate. Table I gives some typical parameters for each of these three systems, based on information provided to the NRC[1].

TABLE I
Parameters for Three Proposed LMDS Systems

Parameter	Hub Station	Subscriber Station
Suite 12/CellularVision		
Modulation	FM Video	Digital
Output Power	-5 dBW/channel	-41 to -21 dBW
Antenna Gain	12 dBi	31 dBi
Bandwidth	18 MHZ	0.01 to 1 MHZ
Cell Radius	4.8 km	4.8 km
VideoPhone/Endgate		
Modulation	Digital	Digital
Output Power	-70 to -4.8 dBW/channel	-78 to 0 dBW
Antenna Gain	29.7 dBi	38 dBi
Bandwidth	6 to 20 MHZ	1.5 to 100 MHZ
Cell Radius	0.8 km	0.8 km
Texas Instruments		
Modulation	Digital, FM Video	Digital
Output Power	0 to -22 dBW/channel	0 to -32 dBW
Antenna Gain	15 dBi	35 dBi
Bandwidth	5.2 to 52 MHZ	5.2 to 52 MHZ
Cell Radius	5.0 km	5.0 km

FSS service links in the 28 GHz band studied included LEO and GEO satellite data networks, such as Spaceway[3], Teledesic[4], Loral Cyberstar[5], and ACTS[6], and LEO and MEO voice/data networks such as Iridium[7], and Globalstar[8]. Spaceway and Teledesic use Ka-band links between satellite and user. ACTS is currently operating Ka-band links to VSAT, USAT, and high data rate terminals, while Iridium, Globalstar, and other LEO systems use Ka-band feeder links.

The two most significant sources of interference which could exist between LMDS and FSS systems are interference from FSS uplinks into LMDS receivers, and interference from LMDS hubs and/or subscriber transmitters into satellite receivers. The second case involves the calculation of the aggregate effects of potentially thousands of LMDS hubs and millions of LMDS subscriber transmissions interfering with LEO satellite receivers and was analyzed by other participants of the NRC. NASA Lewis's role involved the study of interference from FSS uplinks into LMDS receivers. Systems requiring only feeder links at Ka-band require relatively few Ka-band ground terminals, which can be located safely away from LMDS cells. Thus, this study considers systems such as Spaceway, Teledesic, and Cyberstar, which intend to communicate at Ka-band directly with millions of subscribers located within LMDS cells.

Analysis of FSS Interference Into LMDS Receivers

Lewis performed computer simulations of various FSS/LMDS interference scenarios in order to determine the levels of interference experienced by LMDS subscriber terminals and the resultant system availability. (Availability is defined here to be the probability that the C/(N+I) ratio in the worst video channel for a randomly located LMDS subscriber meets or exceeds a given threshold - in this case 13 dB.) The results described here are for the case of Teledesic, Spaceway, and Cyberstar FSS terminals interfering into CellularVision LMDS subscribers. In general, they show that unacceptable C/I levels will exist for a substantial portion of LMDS cells for many cases.

Table 2 presents the availability for these systems for various FSS terminal concentrations. From Table 2 it can be seen that availability is dependent on both FSS terminal density and, for a given FSS terminal type, the corresponding size of the "protection zone" around an LMDS subscriber. (For a given set of FSS/LMDS parameters, the protection zone defines an area around the LMDS subscriber within which an FSS terminal will cause excessive interference.) It is possible to have a high density of FSS terminals and still have relatively high LMDS availability if the protection zone around any single LMDS subscriber is small (e.g. 16 kbps TST terminal). Conversely, it is possible to have a low density of FSS terminals and yet have relatively low LMDS availability if the protection zone around an LMDS subscriber is large (e.g. T1 Spaceway terminal). Also it can be seen that in the case of narrowband FSS interference, availability is strongly affected by whether C/(N+I) is computed on a "best case" power basis or a "worst case" power density basis. Depending on the degree of terminal clustering, availabilities for the two approaches can differ up to 85%.

As would be expected, LMDS availabilities for Spaceway and Cyberstar are much higher (near 100%) than those for Teledesic under *non-clustered* conditions since the spot beam areas for these two systems are much larger than an LMDS cell (by a factor of 4590). Under realistic conditions, however, in which FSS terminals will likely be concentrated in the same high population density areas as LMDS within an FSS spot beam (as opposed to being uniformly randomly located over the entire spot beam area), LMDS availabilities for Spaceway and Cyberstar interferers are substantially worse than for Teledesic (e.g. 95.6% vs 99.85% for terminal concentrations in an area the size of a Teledesic spot beam).

When larger numbers of FSS terminals associated with multiple GEO FSS systems under 2° satellite spacing are considered, LMDS availability can fall below 90%. These results are described in more detail in the following paragraphs.

Note that Table 2 lists the availability based on two different approaches for calculating interference. These are described in NRC Working Group 1 report. In the first approach, the interference power "I" is simply the total interference power falling within the receive channel bandwidth B. In the case of narrowband interference, "I" is found by simply summing the powers of the individual narrowband interferers who fall within the band. Hence, the C/(N+I) ratio is a true power ratio. In the second approach, the total power "I" calculated above is multiplied by the factor B/B_I (B_I is the interferer bandwidth). The power ratio $C/(N+I(B/B_I))$ is then equivalent to the power density ratio $C_o/(N_o+I_o)$ by dividing numerator and denominator by B. Note that since the factor B/B_I is greater than one for narrowband interferers, the power density approach is an upper bound on the interference while the in-band power approach is a lower bound on the interference. Availabilities based on $C_o/(N_o+I_o)$ therefore represent conservative or "worst case" estimates while those based on C/(N+I) represent optimistic "best case" estimates.

It turns out that for the Teledesic T1 case, interference from FSS terminals in adjacent LMDS cells is negligible. This can be explained by Figure 1 which shows the protection zone around an LMDS subscriber which is being interfered with by a T1 Teledesic VSAT. Availability is directly related to both FSS terminal density and the size of the protection zone around the LMDS subscriber. The lower the density and the smaller the protection zone, the higher the availability. (This is simply due to the fact that there is less chance of an FSS terminal falling within the protection zone of an LMDS subscriber, the smaller the protection zone is and the fewer terminals there are.) Looking at Figure 1, the only time the subscriber will suffer harmful interference is when one or more T1 VSATs falls into the narrow lobe protection zone. Since the protection zone does not extend beyond the cell border, interference from VSATs outside the cell is negligible. (It should also be noted that the protection zone size is also a function of the subscriber's distance from the hub. The size will decrease as the subscriber moves closer to the hub since the desired signal power will increase and he is able to tolerate more interference. The protection zone shown in Figure 1 is at its maximum size, since it is for a subscriber on the cell border. The relatively small protection zone and the small number of active terminals (15) leads to the relatively high availabilities shown in the table.

The availabilities for the narrowband Teledesic 16 kbps terminal case are also relatively high despite the large number of active terminals (1440). Again, this can be related back to protection zone size. Figure 2 shows the protection zones around an LMDS subscriber which is being interfered with by a 16 kbps Teledesic terminal. Note that there are two zones shown since this represents a narrowband interference situation. The lobe indicated by the dotted line represents the "worst case" protection zone when interference is treated on a power density basis. The very small lobe within it represents the "best case" protection zone when interference is treated on a power basis alone. The difference in size between the two protection zones accounts for the large differences in availability.

TABLE 2, Part 1

Availabilities for Teledesic, Spaceway, and Cyberstar FSS Interference into CellularVision LMDS Subscriber

Terminal Type/No.	Clustering	Availability based on C/(N+I)	Availability based on Co/(No+Io)
15 active Teledesic T1 TSTs[a]	None (over 53 km x 53 km satellite cell)	NA	99.85%
	8-LMDS cells	NA	98.71%
	4-LMDS cells	NA	97.43%
	2-LMDS cells	NA	95.10%
1440 active Teledesic 16 kbps VSATs	None (over 53 km x 53 km satellite cell)	99.70%	85.28%
	16-LMDS cells	99.30%	54.97%
	8-LMDS cells	98.48%	32.74%
	4-LMDS cells	96.64%	17.15%
	2-LMDS cells	93.83%	8.19%
240 active Spaceway T1 VSATs[b]	240-LMDS cells[c]	99.19%	87.28%
	64-LMDS cells[d]	96.63%	55.43%
	24-LMDS cells[e]	92.17%	29.53%
	16-LMDS cells	88.20%	19.54%
	8-LMDS cells	77.79%	10.68%
	4-LMDS cells	59.10%	5.16%
	2-LMDS cells	35.85%	2.69%

[a] The number of active terminals per satellite is determined as follows. During a Teledesic satellite spot beam dwell time over a satellite cell, the uplink can accommodate up to 1440 basic (16 kbps) FDM users. Since a T1 data rate is 96 times the basic channel data rate, 15 (1440/96) simultaneous active T1 users are possible within a satellite cell. Although the T1 data rate is 1,544 Mbps, Teledesic's FDMA/TDM uplink multiple access method results in a T1 user burst bandwidth of 26.5 MHZ.

[b] 240 active T1 terminals within a spot beam is arrived at as follows. With the Spaceway spot beam bandwidth 120 MHZ and the T1 user bandwidth 2 MHZ, the spot beam capacity per polarization per satellite is 60. In the Spaceway system there are four satellites planned over North America - Nos. 1 and 2 at 101° W and Nos. 3 and 4 at 99° W. Nos. 1 and 3 provide coverage over the 29.5-30.0 GHz band which is outside LMDS. Nos. 2 and 4 provide overlapping spot beam coverage over the 29.0-29.5 GHz band, while Nos. 1 and 2 provide overlapping 120 MHZ spot beam coverage on orthogonal circular polarization. Hence, up to 240 T1 terminals can be simultaneously active within the same spot beam.

TABLE 2, Part 2

Terminal Type/No.	Clustering	Availability based on C/(N+I)	Availability based on Co/(No+Io)
480 active Cyberstar 384 kbps VSATs (77 cm terminals)[f]	240-LMDS cells	99.87%	64.47%
	64-LMDS cells	95.58%	23.70%
	24-LMDS cells	89.37%	10.04%
	16-LMDS cells	83.37%	6.57%
	8-LMDS cells	69.90%	3.32%
	4-LMDS cells	48.19%	1.66%
	2-LMDS cells	27.26%	0.66%
Multiple FSS Systems. 26 Spaceway-type systems with a total of 3120 FSS terminals.[g]	None (terminals rand-only located over 1° spotbeam area)	99.55%	93.42%
	Terminals concen-trated in 10 SMAs or 240 LMDS cell area[c].	89.25%	16.15%

[c] This concentration is based on the average number of SMAs (statistical metropolitan areas) within a 1° spot beam. The average area of an SMA is approximately equal to 24 LMDS cells (1737 km^2). 250 SMAs in CONUS and 24 1° spot beams covering CONUS yield an average of 10 SMAs per spot beam. Thus, 240 active terminals are assumed to be concentrated in an area equal to 10 SMAs or 10 x 24 = 240 LMDS cells.

[d] This clustering corresponds to concentrating the terminals in an area equivalent to a Teledesic satellite spot beam (53 x 53 km).

[e] This clustering corresponds to concentrating the terminals in an area equivalent to an average size SMA (1737 km^2, or 41.7 x 41.7 km).

[f] 480 active Cyberstar (384 kbps) terminals within a spot beam is arrived at as follows. Cyberstar will provide 20 (120 MHZ) spot beams covering CONUS, Alaska, and Hawaii. Each spot beam is essentially 2 overlapping spot beams operating on orthogonal circular polarizations over separate 120 MHZ portions of the uplink frequency band, yielding 240 MHZ of uplink bandwidth over each spot beam geographic area. With each 384 kbps user requiring 50 kHz of bandwidth, 480 simultaneous active Cyberstar terminals are possible within the same spot beam geographic area.

[g] 3120 active T1 (Spaceway-type) terminals within the same spot beam is arrived at as follows. The spot beam capacity for a single Spaceway-type spacecraft is 120 T1 terminals. High population density areas on the East coast of the U. S. can see geostationary satellites along the 57° W - 110° W arc with >30° elevation angle. Assuming 2° spacing along this arc, 26 satellite positions are possible. FSS terminals communicating with these satellites are able to be located in the same geographic area and share the same spectrum by virtue of the 2° spacing and FSS terminal antenna discrimination. This yields a total of 26 x 120 = 3120 simultaneously active T1 terminals within the same 1° spot beam.

LMDS Parameters for Figures 1-4:

Hub EIRP: 10.8 dBW   Sub. Rec. Peak Ant. Gain: 31.0 dBi
Channel BW: 18.0 MHZ   Thermal Noise Power: -125.4 dBW
Cell Radius: 4.83 km (3 miles)   Rec. Carrier Power: -93.56 dBW

Teledesic T1 TST Parameters for Figure 1:

Transmit Power: 0.85 dBW   Signal BW: 26.5 MHZ (TDMA)
Xmit Ant. Gain: 36.0 dBi   Sidelobe Discrimination: -38.2 dB
Xmit Ant Size: 27 cm   Antenna Elevation angle: 40 degrees

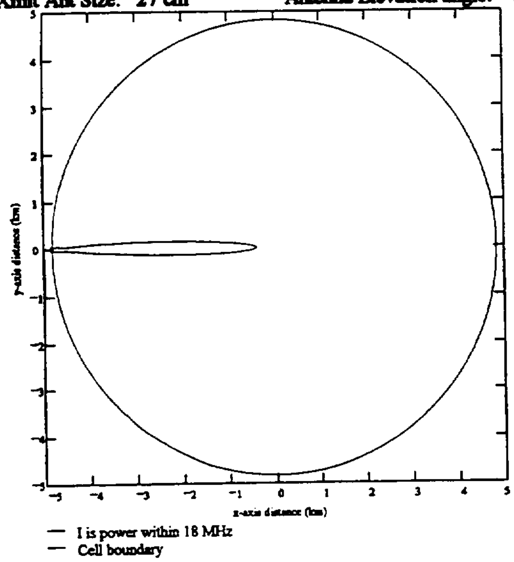

Figure 1 - Protection zones for a CellularVision subscriber receiver being interfered with by a T1 Teledesic TST VSAT.

Teledesic 16 kbps TST Parameters for Figure 2:

Transmit Power: -19 dBW   Signal BW: 225 kHz (TDMA)
Xmit Ant. Gain: 36.0 dBi   Sidelobe Discrimination: -38.2 dB
Xmit Ant Size: 27 cm   Antenna Elevation angle: 40 degrees

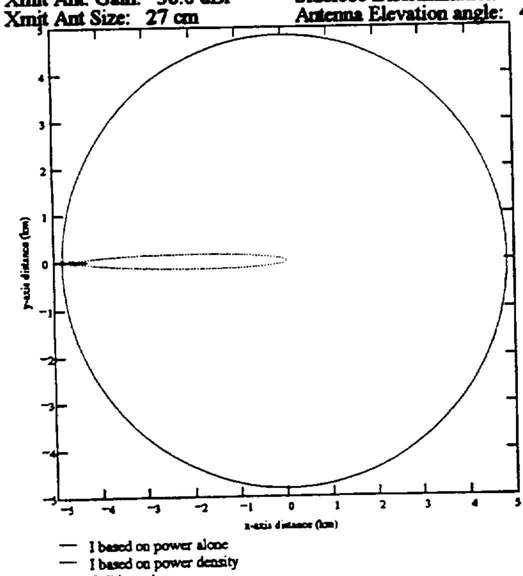

Figure 2 - Protection zones for a CellularVision subscriber receiver being interfered with by a 16 kbps Teledesic TST VSAT.

Max. Allowed I in Channel BW: -106.62 dBW
Required C/(N+I) (clear sky): 13.0 dB
Subscriber Location: Edge of Cell

Cyberstar 70 cm 384 kbps VSAT Parameters for Figure 3:

Transmit Power: 0.0 dBW   Signal BW: 500 kHz (FDMA U/L)
Xmit Ant. Gain: 44.5 dBi   Sidelobe Discrimination: -47.7 dB
Xmit Ant Size: 70 cm   Antenna Elevation angle: 30 degrees

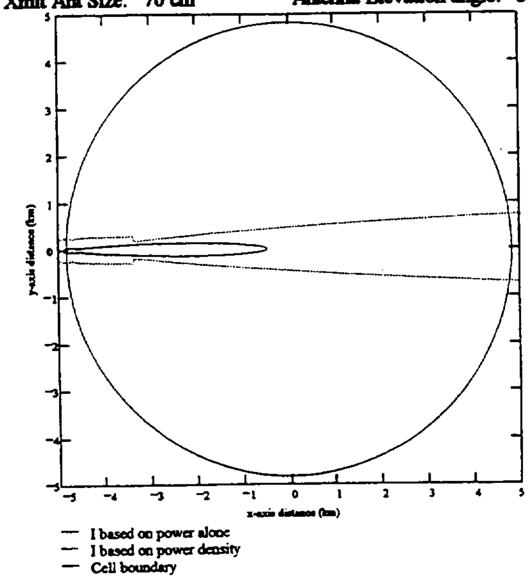

Figure 3 - Protection zones for a CellularVision subscriber receiver being interfered with by Cyberstar 70 cm 384 kbps VSAT.

Spaceway T1 VSAT Parameters for Figure 4:

Transmit Power: 0.8 dBW   Signal BW: 1.08 MHZ (FDMA)
Xmit Ant. Gain: 44.2 dBi   Sidelobe Discrimination: -47.1 dB
Xmit Ant Size: 66 cm   Antenna Elevation angle: 30 degrees

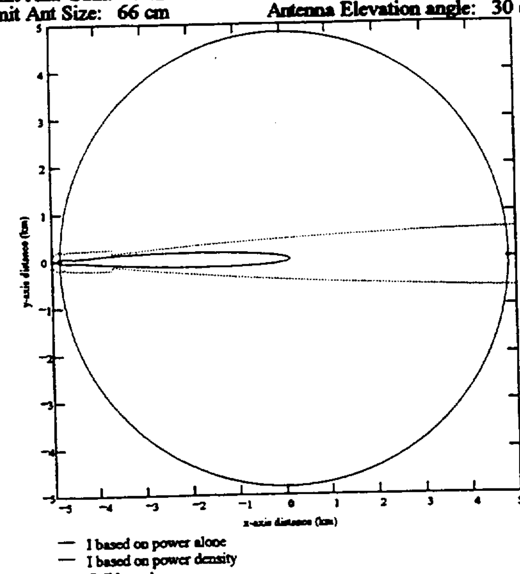

Figure 4 - Protection zones for a CellularVision subscriber receiver being interfered with by a T1 Spaceway VSAT.

availabilities for Spaceway and Cyberstar are only listed for clustered situations since their availabilities under non-clustered conditions are near 100% when a uniform random distribution of FSS transmitters and LMDS receivers is assumed throughout the FSS spot beam area. This is due to the large size of the FSS spot beams compared to the LMDS cell area. Such an assumption, however, is not very realistic since the high traffic density for both FSS and LMDS services will likely occur in the same, more highly populated areas within the FSS spot beam. For example, when FSS terminal concentrations over an area equivalent to 10 SMAs (Statistical Metropolitan Areas) are considered, best case availabilities are 99.19% for Spaceway interference and 98.87% for Cyberstar terminal interference. For clustering over an area equivalent to a Teledesic satellite cell (i.e. 64 LMDS cells), it can be seen that LMDS availabilities are significantly worse for Spaceway and Cyberstar than Teledesic. This is true despite the fact that there are far fewer Spaceway terminals (240) or Cyberstar terminals (480) than, for example, Teledesic narrowband terminals (1440). The best availability for Cyberstar is only 95.58% while that for Teledesic (16 kbps) is 99.7% even though there are 3 times as many Teledesic interfering terminals. Again, this is due to the difference in protection zones for the two types of terminals. Figure 3 shows the protection zones around the LMDS subscriber when he is being interfered with by a 384 kbps Cyberstar terminal. The dotted line is the worst case protection zone (seen to extend beyond the cell boundary) while the solid line is the best case protection zone. Even this best case protection zone, however, is much larger than the one for Teledesic. Hence, even though there are far fewer terminals in the Cyberstar case, the probability that at least one will fall within an LMDS subscriber's protection zone is much larger. This leads to the lower availability.

Figure 4 shows the protection zones for the case of Spaceway T1 interference. Note that the protection zone sizes are about the same as those for Cyberstar. The fact that there are only half as many terminals (240 vs 480) leads to somewhat higher availabilities.

The last entries in the table are for the case of FSS terminals uplinking to multiple FSS satellites spaced 2° apart in the geostationary arc. For example, high population density regions on the East coast of the U.S. are able to see geostationary satellites along an arc of 57°W - 110°W longitude with better than a 30° elevation angle. With a 2° spacing along this arc, 26 satellite positions are possible. The availabilities in the table assume that the FSS terminals communicating with these satellites have characteristics similar to those of the Spaceway system and are uniformly randomly located throughout a common 1° spot beam geographic area. Assuming that the spot beam bandwidth for each system is 120 MHZ (on each of two orthogonal polarizations) and that the uplink access for each system is FDMA, the uplink capacity per satellite per spot beam is approximately 120 T1 users (2 MHZ per T1 user). This leads to a total of 3120 simultaneously active T1 users for all 26 satellites. Under the best case assumption that these terminals are uniformly randomly located over the entire 1° spot beam area (about 332000 km^2), the LMDS availability is about 99.5%. If it is assumed that they are concentrated in an area equivalent to 10 SMAs (equivalent to 240 LMDS cells), then the availability drops to 89.25%.

The simulation results therefore are consistent with what one would expect when both FSS terminal density and protection zone size are considered. In cases where the protection zone does not extend beyond the LMDS cell border, the impact of adjacent cell interference is negligible. The results also indicate that even under best case conditions (i.e. use of the lower bound on interference), a moderate concentration of FSS terminals can yield unacceptable availability to LMDS.

Laboratory Test of Interference Perceptibility

Previous studies performed by NASA Lewis and others have indicated C/I levels which allow acceptable television quality[9,10,11]. These have included FM, AM, and digital video systems. In general, these and other studies have emphasized wideband interference, where the bandwidth of the interferer is considerably larger than the carrier bandwidth. However, in a number of the proposed satellite systems being studied here, the transmitted signal which may interfere with an LMDS receiver may be of a bandwidth comparable to or smaller than the desired video signal bandwidth (e.g., 18 MHz for FM). In some proposed satellite systems (such as Spaceway), the potentially interfering signals may be continuous T1 rate signals in an FDM architecture, QPSK modulated for a signal bandwidth of 1.5 MHz. In other systems they may be bursted signals of various information data rates in an FDM/TDMA architecture, spread over a wider bandwidth, such as 26.5 MHz for Teledesic, or 27.5 MHz for ACTS.

In the case of wideband interference, the interfering spectrum is distributed fairly evenly across the video signal spectrum, resulting in interference which behaves like wideband noise. For smaller bandwidth interference, the spectral structure of the interferer causes a variation in interference levels relative to the video signal band (in most cases power is concentrated at the center of the interferer spectrum) and the effects of the interference become a function of the relative frequencies of the interferer and desired video signal. Narrowband interferers approach the behavior of a CW interferer, affecting certain aspects of the video signal, such as a particular color. In such cases the perceptibility of interference varies with the C/I depending on where in the video spectrum the interference exists.

The reason for investigating these details further is that previous standards used to develop protection ratios for video transmission are inadequate for the FSS/LMDS case. The interference problem may include several satellite systems, transmitting some time-varying combination of narrowband FDM and wider bandwidth TDM signals. To deal with the complexity of the problem, at least for the purposes of the FCC Negotiated Rulemaking Committee, the interference problem is considered in terms of total carrier power to total interferer power ratios. Protection ratios developed for wideband interference, which assume a uniform interference distribution across the desired signal bandwidth, may underestimate the effects of interference in which spectral shape concentrates interferer power at a significantly higher power level. On the other hand, an assumption of a continuous interferer may overestimate the effects of a TDMA bursted type of interferer.

A laboratory investigation was undertaken at NASA Lewis to investigate more closely the C/I levels which cause perceptible interference to an FM video signal for the narrowband interference case. A Ka-band satellite system testbed, part of NASA's Advanced Space Communications

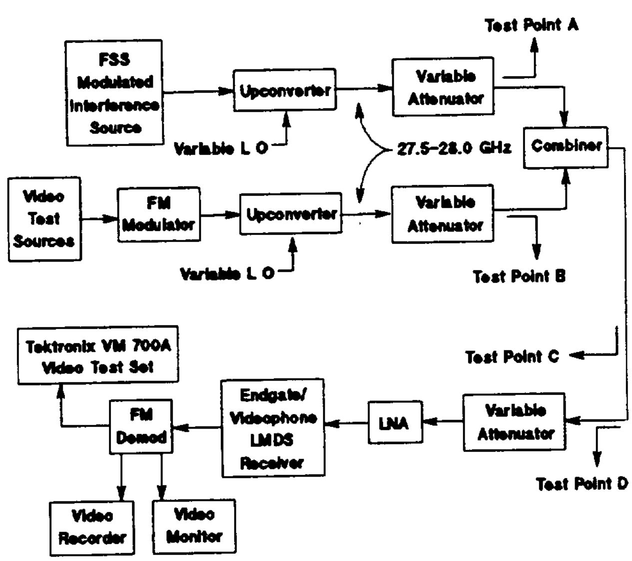

Figure 5 - Simplified block diagram of interference perceptibility test setup.

Laboratory, was modified to provide test and interference signals at 28 GHz, allowing the use of a prototype LMDS subscriber receiver in the test. A simplified block diagram of the test setup is shown in Fig. 5.

The diagram shows how two independent test signals were generated; one is the desired FM-modulated video test signal and the other is the interferer. The video test sources consisted of a video test signal generator and video cassette recorder and provided either standard video test patterns, still images, or motion video. The interference sources consisted of a 27.5 Mbps MSK modulator, operated in either continuous or TDMA mode at selectable burst rates, or up to three independent QPSK T1-rate modulators, with pseudorandom digital data input. A variable local oscillator in the upconverter section allowed the desired and interfering signals to be varied in frequency. After system checkout and calibration, the desired signal center frequency was fixed at 27.68 GHz and the interferers were varied in frequency relative to the desired signal. Variable attentuators allowed the relative power levels of the desired and interfering signals to be adjusted to obtain a range of C/I, and to vary the input to the LNA to adjust the receiver carrier-to-noise ratio (C/N).

The perceptibility of interference was assessed by expert viewers performing subjective testing in a procedure similar to the FCC's Advanced Television Test Procedures for subjective testing[13] (constraints on time and the number of available expert viewers made exact compliance with the FCC procedures infeasible). Each test consisted of a particular receiver C/N, interferer frequency, and range of C/I. The C/I was varied starting above perceptibility and decreased until the interference on the video test signal was perceived by the viewers, then increased from a point well below perceptibility until the interference was no longer perceived. The process was repeated and resulting C/I averaged to obtain the perceptibility threshold. The results of the testing are summarized in Figs. 6-8.

Fig. 6 shows the results of testing using the 27.5 Mbps modulation interference. Each point on the plot indicates the maximum C/I level at which interference was perceived by the expert viewers as a function of the interferer center frequency offset relative to the video signal center. Three sets of data are plotted. In one, the interfering signal was a continuous 27.5 Mbps signal. In the second, the 27.5 Mbps signal was bursted at a rate equivalent to 4 T1 signals (4 x 1.544 = 6.176 Mbps, or 22.5% duty cycle). In the third, the 27.5 Mbps signal was bursted at a rate equivalent to one T1 signal (1.544 Mbps, or 5.6% duty cycle). For the bursted cases, the C/I was based upon a measurement of the peak

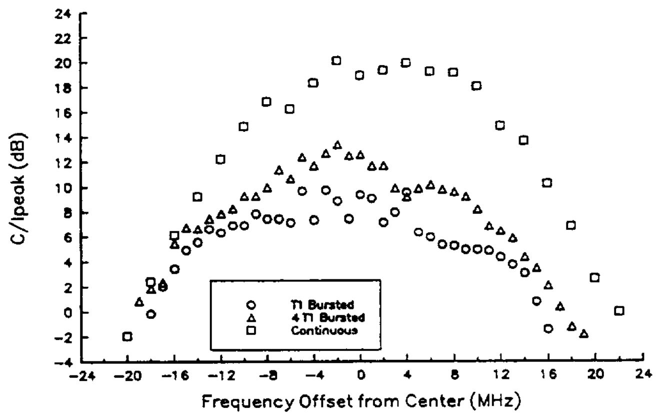

Figure 6 - Interference perceptibility threshold for a continuous and bursted 27.5 Mbps MSK-modulated interferer; receiver C/N was 31 dB.

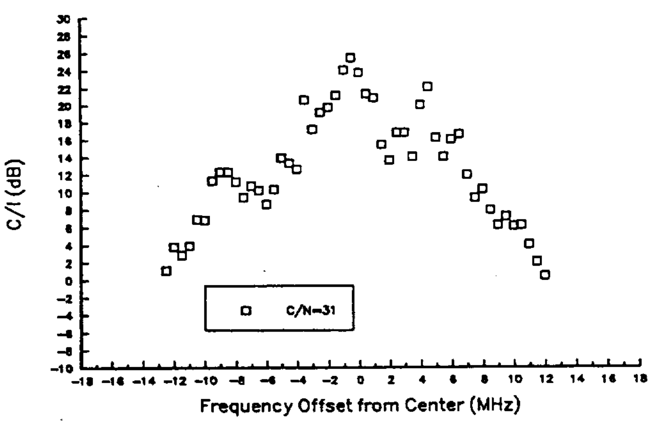

Figure 7 - Interference perceptibility threshold for a continuous T1-rate QPSK-modulated interferer; receiver C/N was 31 dB.

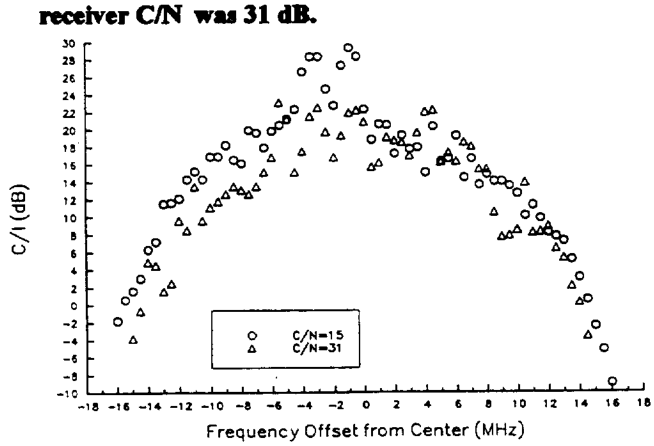

Figure 8 - Interference perceptibility threshold for three continuous T1-rate QPSK-modulated interferers and receiver C/Ns of 15 and 31 dB.

power, rather than the average power, of the interferer. For all cases, the receiver C/N was 31 dB.

The results show that the C/I perceptibility threshold varies as the interfering spectrum is moved across the video signal spectrum, with the highest C/I at the middle of the spectrum. The spectral shape of the interferer, with power concentrated at the center of the spectrum increases this effect compared to wideband interference in which the interferer power is assumed flat across the desired signal band. For example, if a flat interferer spectrum were assumed (with 41 MHz bandwidth), the difference in perceptibility between the 0 MHz and 20 MHz offset points would be about 3 dB; the measurement using the 27.5 Mbps spectrum yielded a difference of about 17 dB. The data also indicates a significant difference in perceptibility between the continuous and bursted interference. The 4 x T1 bursted interference is perceived at C/I's of 5-10 dB lower than the continuous interference; the average power of the 4 x T1 interferer is about 6 dB lower. The T1 bursted interference, another 6 dB lower in average power, is perceived at C/I's of 2-4 dB lower than the 4 x T1 case.

The continuous QPSK-modulated T1 case is shown in Fig. 7. In this case, the interferer bandwidth (main spectral lobe) is 1.544 MHz, less than 10% of the video signal bandwidth. The significance of this case is the variability in perceptibility threshold as a function of interferer frequency offset. With the interferer power concentrated in a narrow bandwidth, the interference can be perceived at C/I's as high as 25 dB or as low as 8 dB, within the 18 MHz video signal bandwidth. In a shared FSS-LMDS band, the protection ratios must be based upon the worst case for narrowband interference. Note by comparison with Fig. 6, where the maximum perceptible C/I is about 20 dB, that the required increase in protection ratios will be 5 dB or more.

In Fig. 8, three continuous QPSK-modulated T1 signals, located in adjacent channels (2.5 MHz spacing), are tested, at two receiver C/N's. The 15 dB C/N represents a C/N at the edge of an LMDS cell (there is a range of cell-edge C/Ns for different proposed LMDS systems of about 13 to 19 dB). The data shows that at the lower C/N, the C/I for interference perceptibility is 0 to 6 dB higher; interference is more easily perceived at the cell edge where operating C/N is lower. This is another factor which must be taken into account in determining protection ratios.

The effect of multiple T1 FDM signals existing within a single FM video bandwidth can be seen by comparing Figs. 7 and 8. The C/I is measured using total interferer power, where the three T1 signals are measured together as one

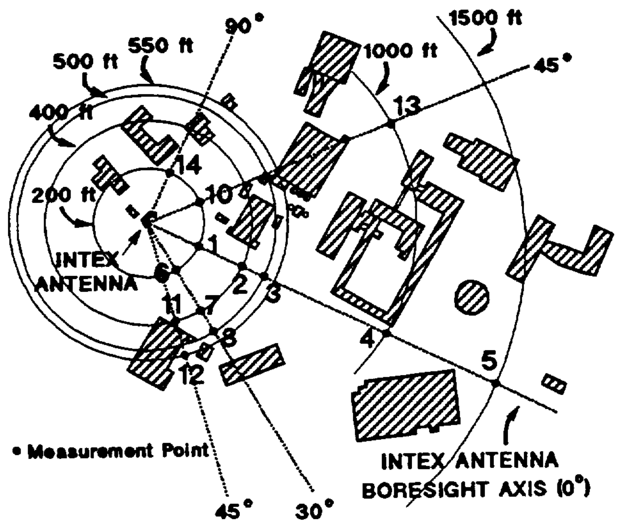

Figure 9 - Distribution of field test points relative to the INTEX antenna and NASA Lewis physical structures.

interferer. In spreading out the interferer power over three T1 bandwidths, the maximum C/I for perceptibility decreases by about 3 dB, but the variation across the band changes such that C/I varies up to about ± 6 dB.

The laboratory perceptibility test results established the increased sensitivity of the FM video signal to narrowband interference compared to wideband interference. Signal power concentrated at the center of an interferer spectrum results in higher interference protection ratio requirements. In particular, very narrowband interferers can significantly increase the protection ratio requirement because some portions of the FM video spectrum are more sensitive to interference in terms of perceptibility. The threshold C/I's measured are in many cases higher than the 13 dB protection ratio assumed for the analysis above, hence, the LMDS availability may be even lower than calculated.

Field Tests of the 28 GHz Reflection Environment

The only currently operational Ka-band satellite in the Western Hemisphere is NASA's ACTS. With the ACTS control center and several operational Ka-band ground terminals at NASA Lewis, it was possible to obtain a set of field measurements of the signal reflection environment in the vicinity of a Ka-Band terminal.

The importance of the signal reflection environment is twofold. First, LMDS systems implemented in urban environments may experience blockages in the line-of-sight from the cell hub to the LMDS subscriber. The existence of reflected signals will offer alternative paths for LMDS receivers. Second, the analysis of FSS-LMDS interference has taken into account only line-of-sight radiation from the FSS antenna to LMDS receivers. However, the existence of significant reflected signals complicates this analysis and makes it possible that significant interference will exist on other than line-of-sight paths. The purpose of the NASA Lewis field tests was to verify qualitatively that the reflection environment supports these assumptions.

The Ka-band ground terminal chosen for these tests was NASA's INTEX Ka-band Experiment Terminal. Fig. 9 shows the terminal location and surrounding physical structures (shown as cross-hatched boxes). The location of 13 test points is shown, on lines radiating from the antenna at angles of 0°, 30°, 45°, and 90° from the antenna boresight axis, and at distances of 200, 400, 500, 550, 1000, and 1500 feet from the antenna. Test point locations were constrained by the physical environment. The INTEX terminal is designed for high data rate (up 300 Mbps) communications with ACTS, transmitting 40 Watts through a 2.44 meter parabolic reflector antenna. The boresight EIRP is 68.2 dBW. The antenna is at ground level and inclined at 31.8°, transmitting a vertically polarized signal.

Field measurements were made with the INTEX terminal transmitting a CW signal at 29.2 GHz (the ACTS operational band is 29.1-30.0 GHz). The received power was measured with three different receive antennas. A NASA-developed 16 X 16 element planar array (23 dB gain) and a standard pyramidal horn (24.7 dB gain) were used for all tests. Late in the testing period a third antenna, a 32 x 32 element planar array (22 dB gain), developed by the Endgate Corp. as an LMDS antenna prototype, became available. The Endgate antenna was tested at Points 1, 2, and 3. A spectrum analyzer served as the receiver.

At each test point, measurements were made in six directions: pointing directly at the INTEX antenna along the line connecting the test point and the antenna, and at ±45°, ±90°, and 180 from this line (+45 and +90 indicate clockwise rotation). Measurements were made with the receive antenna polarization oriented both vertically and horizontally. The receive antenna was swept through elevation angles of 0° to 30 and the maximum signal observed was recorded. For direct pointing the maximum signal was observed at elevation angles of 0° to 5°, but for reflected signals the maximum could be found at elevation angles up to 30°. The results are listed in Tables 3-6.

The data presented below indicates a complex interference environment. Considering the INTEX antenna size and transmit frequency, the far field can be calculated to be >3700 feet, thus all of the measured points are within the near field of the INTEX antenna. The near field varies significantly in intensity[14] with distance. For example, note in Table 3 that the received power (0° direction) at a distance of 400 feet is up to 10 dB higher than at 200 feet. The transmit antenna sidelobes are depolarized, resulting in significant variation in received power between horizontal and vertical polarizations at various points. The reflective structures in the vicinity of the antenna further complicate the picture.

Significant received power levels were measured at distances up to 1500 feet, and at all angles from the INTEX boresight axis. The presence of reflecting structures results in significant received signal power, regardless of the direction in which the receive antenna is pointed, indicating a very rich and complex reflection environment. Two measurement points worth noting are points 12 and 13, both of which are completely blocked from a line-of-sight to the INTEX antenna. Point 12 has obvious reflective paths which allow received power to be measured in all directions (see Fig. 9). At point 13, where no obvious reflective paths exist, no received signal was observed.

Table 3, Part 1- Measurements along the INTEX Boresight Axis - Received Power [dBm]

[Point] Distance		[1] 200 ft		[2] 400 ft		[3] 500 ft	
Polarization		V	H	V	H	V	H
0°	Lewis	-58	-56	-55	-48	-61	-50
	Horn	-59	-52	-50	-40	-59	-47
	Endgate	-44	-64	-55	-48	-63	-52
+45°	Lewis	-66	-66	-67	-67	-68	-63
	Horn	-75	-64	-78	-59	-82	-68
	Endgate	-69	-57	-58	-66	-68	-75
-45°	Lewis	-63	-52	-64	-61	-65	-49
	Horn	-84	-74	-74	-66	-87	-74
	Endgate	-61	-66	-58	-60	-61	-66
+90°	Lewis	-70	-56	-67	-57	-70	-60
	Horn	-82	-67	-82	-70	-85	-73
	Endgate	-58	-64	-64	-61	-70	-66
-90°	Lewis	-68	-61	-67	-66	-72	-71
	Horn	-82	-81	-80	-70	-88	-76
	Endgate	-63	-61	-64	-62	-68	-68
180°	Lewis	-76	-68	-78	-78	-78	-81
	Horn	-50	-68	-80	-80	-91	-85
	Endgate	-75	-78	-71	-71	-79	-75

Table 3, Part 2

[Point] Distance		[4] 1000 ft		[5] 1500 ft	
Polarization		V	H	V	H
0°	Lewis Array	-68	-65	-88	-82
	Horn	-65	-55	-79	-77
+45°	Lewis	-71	-71	-89	-88
	Horn	-90	-74	-95	-92
-45°	Lewis Array	-71	-94	-89	-90
	Horn	-91	-76	-93	-88
+90°	Lewis Array	-72	-63	-89	-89
	Horn	-95	-81	-92	-93
-90°	Lewis Array	-76	-69	-90	-85
	Horn	-94	-83	-91	-85
180°	Lewis Array	-87	-76	-91	-88
	Horn	-91	-83	-89	-87

Table 4- Measurements 30° from the INTEX Boresight Axis - Received Power [dBm]

[Point] Distance		[6] 200 ft		[7] 400 ft		[8] 500 ft	
Polarization		V	H	V	H	V	H
0°	Lewis	-55	-45	-62	-67	-80	-77
	Horn	-54	-44	-52	-46	-84	-70
+45°	Lewis	-65	-62	-70	-66	-82	-79
	Horn	-78	-65	-74	-69	-86	-76
-45°	Lewis	-65	-66	-70	-70	-80	-79
	Horn	-83	-67	-84	-71	-73	-78
+90°	Lewis	-72	-69	-76	-71	-86	-84
	Horn	-82	-74	-83	-77	-88	-84
-90°	Lewis	-67	-67	-72	-72	-85	-77
	Horn	-76	-70	-89	-76	-90	-87
180°	Lewis	-77	-77	-75	-81	-82	-77
	Horn	-80	-73	-72	-78	-80	-74

Although no comprehensive quantitative analysis was attempted, the data provided a qualitative verification of the reflection environment in the vicinity of an FSS antenna in the 28 GHz band. This indicates that some interference problems for LMDS receivers beyond what is indicated by a line-of-sight analysis will likely occur. It also indicates the possibility of LMDS receivers operating successfully using indirect reflective paths in urban environments.

Table 5- Measurements 45° from the INTEX Boresight Axis - Received Power [dBm]

[Point] Distance		[10] 200 ft		[11] 400 ft		[12] 550 ft	
Polarization		V	H	V	H	V	H
0°	Lewis	-51	-47	-69	-70	-87	-87
	Horn	-48	-45	-64	-64	-86	-81
+45°	Lewis	-66	-66	-78	-80	-88	-85
	Horn	-80	-70	-79	-76	-87	-82
-45°	Lewis	-63	-57	-80	-78	-91	-83
	Horn	-71	-69	-78	-76	-92	-90
+90°	Lewis	-68	-61	-81	-78	-89	-89
	Horn	-76	-75	-88	-81	-85	-84
-90°	Lewis	-74	-62	-79	-81	-91	-89
	Horn	-74	-70	-76	-79	-93	-92
180°	Lewis	-68	-61	-81	-78	-89	-89
	Horn	-76	-75	-88	-81	-85	-84

Table 6 - Measurements 90° from INTEX Boresight Point 14, Distance 200 ft. - Received Power [dBm]

		0°	+45	-45°	+90°	-90°	180°
H	Lewis	-63	-78	-83	-80	-76	-82
	Horn	-57	-81	-75	-87	-78	-69
V	Lewis	-60	-79	-70	-74	-76	-81
	Horn	-55	-82	-73	-84	-77	-75

Summary

The analyses and test results presented indicate that significant potential interference from FSS uplinks into LMDS receivers will likely exist if the two systems co-share the same frequency spectrum. The analyses indicate that in most cases LMDS system availability will be at unacceptably low levels. Laboratory interference tests show that for narrowband types of interference, the 13 dB C/I protection ratio used in the analyses may be too low to allow acceptable television viewing; a higher protection ratio will further decrease LMDS system availability. Field tests indicate that the expected reflection environment in the vicinity of an FSS uplink terminal will likely expand the area of unacceptable interference levels beyond that shown by the analyses. The NRC concluded, based in part on these results, that co-frequency sharing of the 28 GHz band between FSS and LMDS sysems was not possible.

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13. ABSTRACT ***(Maximum 200 words)***

The Federal Communications Commission (FCC) of the United States completed a Negotiated Rulemaking Committee in September, 1994 to determine methods for frequency sharing of the 27.5 to 29.5 GHz spectrum between terrestrial Local Multipoint Distribution Service systems and Fixed Satellite Service systems. The committee concluded that based on current commercially proven technology, these services could not share the same spectrum, due to expected unacceptable levels of mutual interference. Analysis and laboratory and field tests performed by NASA's Lewis Research Center contributed technical data which was used to support this conclusion. NASA's results indicate levels of carrier-to-interference ratios (C/I) which create perceptible degradation, the levels of C/I which might be expected in typical operational scenarios, and the level of reflected signals which might be found in the vicinity of transmitting FSS ground terminals.

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